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14. ABSTRACT

This report results from a contract tasking FSUF MRTI RAS as follows: Three year cycle of fundamental investigations of plasma dynamic processes with microwave discharge participation fulfilled in the framework of Projects 2429p and 2820p showed availability of principally new scientific direction which blends together electrodynamics, physics of electrical gas discharge and combustion physics.
Investigations in this direction can be continued with a help of modernized setup with application of additional and already developed diagnostic means.

Main tasks of the setup modernizing are: realization of propane-air flammable mixture SS submerged jet of round cross section; realization of SS submerged jet with flat geometry; realization of quasi-optical beam of EM waves for feeding of multi vibrator initiation system; realization of SS air flow with higher temperature.

Proposed project is related to the fundamental investigations. The following results will be achieved within the framework of the project in the experimental and theoretical investigations.

Will be obtained experimental data about deeply undercritical MW discharge influence on the combustion time and combustion completeness of propane-air mixture in dependence on velocity of mix propagation over the plasma region, and also about deeply undercritical MW discharge influence in high-speed flow of propane-air mixture on concentration limits of combustion ignition.

Measurements of the flame front propagation velocity over the high-speed propane-air flammable mixture flow at its ignition by deeply undercritical MW discharge will be carried out.

Will be shown the initiation possibility of deeply undercritical MW discharge in SS airflow by linear electrical vibrator, which is fed by quasi-optical linearly polarized EM beam with non uniform amplitude over its length.

Will be obtained a data about mutual electrodynamic influence of initiating vibrators united in system at burning of deeply undercritical MW discharges in their base parts.

Will be shown possibility of spatially multiple ignition of propane-air flammable mixture with a help of electromagnetically coupled vibrators initiating the deeply undercritical MW discharges.

Enumerated information will allow determining the real prospective of gas mixtures combustion optimization with a help of MW discharge technology in wide range of conditions.

15. SUBJECT TERMS
EOARD, Physics, Plasma Physics and Magnetohydrodynamics

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ISTC Project No. 3572p

(067003)

“Investigation of deeply undercritical microwave discharge plasma influence on combustion processes in propane-air mixture in its high-speed flow”

Final Project Activity Report

on the work performed from September 29, 2006 to September 28, 2009

Federal State Unitary Enterprise “Moscow Radiotechnical Institute of the Russian Academy of Sciences

Warshavskoe shosse, 132, Moscow, Russia , 117519

Project Manager <Igor I.Esakov>
<Ph.D.>

Signature / Date

1. Objectives of the Project, Scope of Work and Technical Approach

1.1 Project goal

Electric gas discharge in microwave (MW) range of electromagnetic (EM) wave range λ in quasi-optical EM beam is realized in different types in different ranges of EM E_0 field initial level and of pressure p.

In **Fig.1.1.1** one can see a realization scheme of such discharges and given parameters at which they can be realized. In this picture we understand under τ duration of EM-radiation.

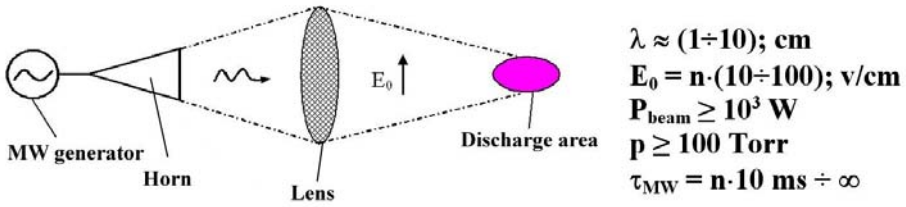

Fig. 1.1.1 Realization scheme of MW generator in quasi-optical EM-beam

For example in Fig.***1.1.2*** we represent E_0-p diagram of different types of MW discharges in air at $\lambda \approx 10$ cm and $\tau = 40$ μs. In the present Report we use a discharge that corresponds to an area **V** of this diagram. It is, so called, deeply subcritical discharge type. It can be realized at sufficiently low field E_0 level and sufficient high air pressure p. Comparably cheap and widespread MW generators with continuous generation mode can be applied for its realization.

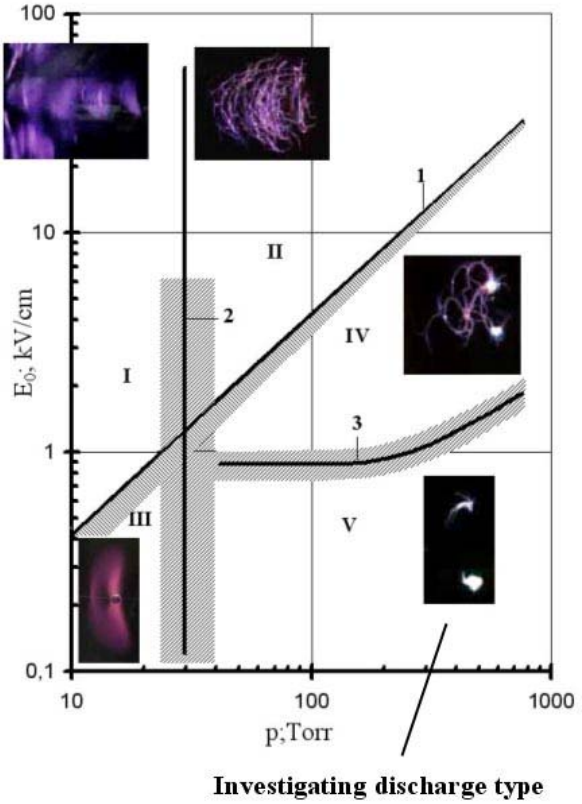

Fig 1.1.2. Electric discharge in quasi-optical electric field types

In the present Report we continue investigations of deeply subcritical MW-discharge in quasi-optical EM beam initiation means with a help of EM vibrators. At that we vary their design: we investigate resonant features of thin linear EM vibrators, namely, tube vibrators with different execution of their ends and tube vibrators with dielectric nozzles (**Tasks 2 and 3**). We vary means of the vibrator (initiating deeply subcritical EM-discharge) excitation by EM- field that (**Tasks 5** and **11**). We vary a scheme of a high-speed flow formation in a stern area of a vibrator (**Tasks 1**, **2**, **3**, **7**). We investigate features of deeply subcritical EM-discharge realized in the stern area of an initiator in the high-speed

flow formed there (**Tasks 8** and **14**). WE investigate a realization possibility of multiple deeply subcritical EM discharges in the high-speed airflow when they are realized by a system of EM-vibrators (**Tasks 4**, **10**, **15**).

In the Project we continue investigations of deeply subcritical EM-discharge plasma impact on combustion processes of model propane-air mixture in its high-speed flow (**Tasks 2**, **7**, **9**, **14**, **15**). At that we varied weight content of propane in the mixture, a flow velocity, its organization, etc.

And finally in the Project we have fulfilled all preparatory works on investigations of deeply subcritical EM-discharge plasma impact on combustion processes of model propane-air mixture in its high-speed "warm" (**Tasks 12**, **16**, **17**, **18 and 19**). At that we have developed a scheme of air heating; its elements have been manufactured, assembled and tested in the applied experimental installation. In tests we have realized the applied discharge type in the warm high-speed airflow.

The process of the experimental investigations was accompanied with theoretical computations and numerical modeling of main investigated phenomena (**Tasks 6**, **13** and **20**).

1.2. Expected results

The Project is attributed to fundamental investigations. Results which have been required to achieve are clearly formulated in Attachment I to the coordinated formulation of the Project in the section **II.2** of detailed information about it.

In the process of the project execution we obtained questions to posed questions, they will be formulated in the main part of the Report.

1.3. Technical approach

Main experiments were carried out with a help of the installation existing in MRTI, which scheme is represented in Fig. **1.3.1**.

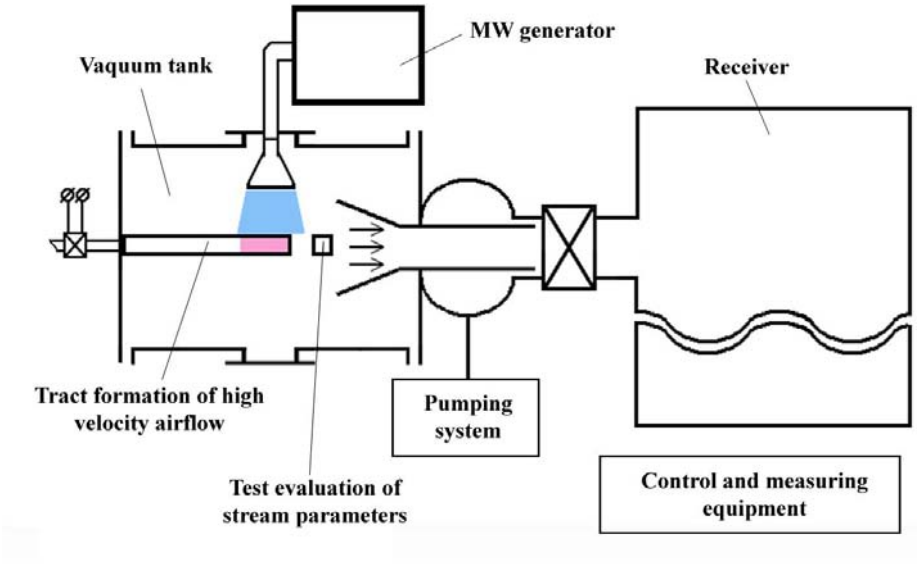

Fig. 1.3.1. A scheme of experimental installation's basic elements

It contains a hermetic working chamber with a receiver. This volume is filled with atmospheric air. Its pressure can be established in a range p=(3-760) Torr. A linearly polarized quasi-optical EM beam with $\lambda\approx$12.5 cm and power $P_{MW}\approx$1kW can be injected to the working chamber of the installation. An initiator of MW discharge is situated in the central area of the chamber. The installation is completed by elements forming a high-speed airflow or its model flammable mixture with propane. An air velocity can be regulated in a range $v_{fl}\approx$(10-500) m/s. In experiments one can realize high-speed and "integral" photo detection of a discharge area, locally measure a flow stagnation temperature T_{stag} and its stagnation pressure p_{stag} . The installation is completed with a device allowing to synchronize in time its separate elements work and setting their time of work, etc.

The installation was modernized and was added by corresponding elements at undertaking of definite experiments.

2. Summary of Technical Progress

2.1. Current Technical Status

Task Subtask	Start (quarter)	End (quarter)	Status / Comments
Task 1	1 Quarter	4 Quarter	Work is completed
Task 2	1 Quarter	4 Quarter	Work is completed
Task 3	1 Quarter	4 Quarter	Work is completed
Task 4	1 Quarter	4 Quarter	Work is completed
Task 5	1 Quarter	4 Quarter	Work is completed
Task 6	1 Quarter	4 Quarter	Work is completed
Task 7	5 Quarter	8 Quarter	Work is completed
Task 8	5 Quarter	8 Quarter	Work is completed
Task 9	6 Quarter	7 Quarter	Work is completed
Task 10	6 Quarter	8 Quarter	Work is completed
Task 11	5 Quarter	7 Quarter	Work is completed
Task 12	5 Quarter	8 Quarter	Work is completed
Task 13	5 Quarter	8 Quarter	Work is completed
Task 14	9 Quarter	11 Quarter	Work is completed
Task 15	9 Quarter	11 Quarter	Work is completed
Task 16	9 Quarter	11 Quarter	Work is completed
Task 17	11 Quarter	12 Quarter	Work is completed
Task 18	9 Quarter	11 Quarter	Work is completed
Task 19	11 Quarter	12 Quarter	Work is completed
Task 20	9 Quarter	12 Quarter	Work is completed

2.2. Tasks of the work plan

Task 1: Modernization of the setup for experimental determination of a deeply undercritical MW discharge plasma influence on combustion time τ_{com} of propane-air mixture.

At the moment of Project realization available experimental installation has been completed by the elements forming the submerged high-speed air stream in its working chamber. On the given problem it was additionally completed by the elements, allowing to include the internal channel of the tubular linear EM-vibrator on an exit of the formation duct of the high-speed stream. The inlet of this duct has been completed by the elements, allowing to form a combustible propane-air mixture with a required proportion of propane in it.

- **Personnel Commitments**

Name	Category	Days
Igor I. Esakov	I	30
Kirill V. Khodataev	I	16
Lev P.Grachev	I	26
Konstantin V. Aleksandrov	I	26
Vyacheslav A. Vinogradov	I	20
Alexander A. Ravaev	I	20
Vyacheslav V. Fedorov	I	30
Nikolay I. Uksusov	I	38
Sergey V. Denisyuk	I	37
Viktor A. Gudovich	I	30
Tatyana A. Mityaeva	I	18

Tamara M. Murinchik	II	22
Aleksander F. Ezhov	III	10
Sergey N.Il'in	III	10
Igor V. Prutskiy	III	10
Aleksander I. Chervonnyi	III	10

Task 2: Experiments on design of electrical vibrator form, which is insuring execution of experiments on deeply undercritical MW discharge plasma influence on combustion time τ_{com} of propane-air mixture

By the moment of the Project realization resonant properties of linear cylindrical EM-vibrators of various diameter with spherically rounded off ends have been investigated. In the performance process of the given problem the geometry of the tubular EM-vibrator - the initiator of gas electric breakdown in the quasi-optical EM-beam with deeply subcritical field level has been developed. As the result the deeply subcritical EM-discharge has been realized in the stern area of this initiator in the high-speed stream.

- **Personnel Commitments**

Name	Category	Days
Igor I. Esakov	I	30
Kirill V. Khodataev	I	16
Lev P.Grachev	I	26
Konstantin V. Aleksandrov	I	26
Vyacheslav A. Vinogradov	I	20
Alexander A.Ravaev	I	20
Vyacheslav V. Fedorov	I	30
Nikolay I. Uksusov	I	30
Sergey V. Denisyuk	I	30
Viktor A. Gudovich	I	30
Tatyana A. Mityaeva	I	18
Tamara M. Murinchik	II	22
Aleksander F. Ezhov	III	10
Sergey N.Il'in	III	10
Igor V. Prutskiy	III	10
Aleksander I. Chervonnyi	III	10

Task 3: Experiments on design of electromagnetic vibrator (initiating the undercritical MW discharge), which has to minimally perturb the aerodynamic parameters of the submerged high-speed air stream

At the moment of the Project realization beginning we have tested the way of air electric breakdown initiation by means of the linear EM-vibrator placed in the quasi-optical MW-beam with deeply subcritical level of the field. In the course of performance of the given problem this way has been applied to realization of deeply subcritical MW-discharge in the submerged high-speed air stream. In experiments such vibrators have been tested at their arrangement over the metal screen in loops of direct and return EM-waves. The developed form of the vibrator and a way of its fastening allow to deform minimally aerodynamic parameters of the stream blowing around it. With its help the deeply subcritical MW discharge has been lighted in the stern area of the vibrator in the high-speed air stream.

- **Personnel Commitments**

Name	Category	Days
Igor I.Esakov	I	30
Kirill V.Khodataev	I	16
Lev P.Grachev	I	26
Konstantin V.Aleksandrov	I	26

Vyacheslav A.Vinogradov	I	20
Alexander A.Ravaev	I	20
Vyacheslav V.Fedorov	I	30
Nikolay I. Uksusov	I	30
Sergey V. Denisyuk	I	30
Viktor A. Gudovich	I	30
Tatyana A. Mityaeva	I	18
Tamara M. Murinchik	II	22
Aleksander F. Ezhov	III	10
Sergey N. Il'in	III	10
Igor V. Prutskiy	III	10
Aleksander I. Chervonnyi	III	10

Task 4: Development, design and manufacturing of elements forming flat submerged high-speed stream of air flowing from the atmosphere into the working part of the setup

By the moment of the beginning of the Project realization experimental installation has been completed by the elements forming the submerged gas stream in its working chamber with round section of d_{out} = 30 mm in diameter. Its parameters on the exit of the Laval nozzle are characterized by the Mach number M = 2 at the speed of airflow in the stream v_{fl} = 500 m/s, static temperature T_{st} = 150 °K and static pressure p_{st} = 100 Torr. In the course of performance of the given problem we have carried out calculations of the air duct elements forming a flat submerged stream. Thus at this stream the specified parameters of the stream with round section were maintained. The designed duct has been manufactured and mounted in the experimental installation. On an exit of the Laval nozzle the stream has the sizes of the transversal cross-section (10x70) mm.

- **Personnel Commitments**

Name	Category	Days
Igor I.Esakov	I	30
Kirill V.Khodataev	I	16
Lev P.Grachev	I	26
Konstantin V.Aleksandrov	I	26
Vyacheslav A.Vinogradov	I	20
Alexander A.Ravaev	I	20
Vyacheslav V.Fedorov	I	30
Nikolay I.Uksusov	I	30
Sergey V.Denisyuk	I	30
Viktor A. Gudovich	I	30
Tatyana A.Mityaeva	I	18
Tamara M. Murinchik	II	22
Aleksander F. Ezhov	III	10
Sergey N. Il'in	III	10
Igor V. Prutskiy	III	10
Aleksander I. Chervonnyi	III	10

Task 5: Development, design and manufacturing of MW antenna system, forming "thin quasi-optical beam" of linearly polarized EM radiation in the working part of the setup

To the Project beginning the experimental installation has been completed by the elements forming linearly polarized quasi-optical EM-beam in its working chamber. The beam was formed by the horn aerial having the form of an obelisk with an entrance rectangular section (90x45) mm, the size of the radiating aperture (90x90) mm and length 150 mm. In the course of performance of the given problem the given horn on the exit has been completed by replaceable nozzles of 50 mm length. These nozzles allow to form a linearly polarized field in a near zone of radiation with a flat phase front with square

transversal cross-section in the size (90x90) mm and "narrow" transversal cross-section along a vector of EM-wave electric component.

- **Personnel Commitments**

Name	Category	Days
Igor I. Esakov	I	30
Kirill V. Khodataev	I	16
Lev P.Grachev	I	26
Konstantin V. Aleksandrov	I	30
Vyacheslav A.Vinogradov	I	20
Alexander A. Ravaev	I	20
Vyacheslav V. Fedorov	I	30
Nikolay I. Uksusov	I	30
Sergey V. Denisyuk	I	30
Viktor A. Gudovich	I	30
Tatyana A.Mityaeva	I	22
Tamara M. Murinchik	II	22
Aleksander F. Ezhov	III	10
Sergey N. Il'in	III	10
Igor V. Prutskiy	III	10
Aleksander I. Chervonnyi	III	10

Task 6: Theoretical support of the experimental investigations. Development of theoretical model of spatially multiple MW deeply undercritical discharge in high-speed flow

In the course of performance of **Tasks 1-5** their theoretical support was conducted. The near field of linear EM-vibrators excited by linearly polarized EM-wave was calculated for vibrators of different length, diameter and the form of performance of the ends. The calculations have shown a possibility of multiple increasing in the amplitude of the induced near field on the ends of vibrators in comparison with the amplitude of a field exciting them. Within the limits of the given problem also is created the computational model of initiation of the linear system of deeply subcritical MW –discharges initiated by EM- vibrators, considering their mutual electrodynamic influence.

- **Personnel Commitments**

Name	Category	Days
Kirill V.Khodataev	I	80
Lev P.Grachev	I	26
Vyacheslav A.Vinogradov	I	54
Alexander A. Ravaev	I	46

Task 7: Experiments on determination of MW deeply undercritical discharge plasma influence on combustion time of propane-air flammable mixture, on concentration limits of its ignition and its combustion completeness

At the moment of the beginning of the present Project realization various plasma chemical processes arising at realization of gas electric discharges have been described. Within the limits of the present problem their influences on characteristics of burning of propane in its mixture with air were investigated at ignition of deeply subcritical initiated MW –discharge in this mixture. Ignition of such a discharge in the stream of propane-air mixture facilitates the task solution. In this case research can be carried out in the trail of the MW-discharge burning area. Experiments and their analysis have shown that the plasma of deeply subcritical discharge is capable to ignite the propane-air mixture. Essentially lean mixture is thus ignited also. In experiments propane burns down completely at the stream speed up to 100-150 m/s. The experimental scheme is characterized by presence of thermal blocking of the stream which was detected and in the experiments. At the same time in experiments the stream throttling effect which allows to overcome the thermal blocking phenomenon has been detected.

- **Personnel Commitments**

Name	Category	Days
Igor I. Esakov	I	22
Kirill V. Khodataev	I	9
Lev P.Grachev	I	22
Konstantin V. Aleksandrov	I	20
Vyacheslav A.Vinogradov	I	15
Alexander A. Ravaev	I	20
Vyacheslav V. Fedorov	I	25
Nikolay I. Uksusov	I	36
Sergey V. Denisyuk	I	25
Tatyana A.Mityaeva	I	20
Tamara M. Murinchik	II	20
Andrey A. Kostyuk	II	6
Dmitry V. Bychkov	II	13
Sergey N. Il'in	III	16
Igor V. Prutskiy	III	16

Task 8: Experiments on determination of MW deeply undercritical discharge properties with application of the initiating vibrator minimally disturbing aerodynamic parameters of submerged air stream

By the moment of realization of the Project it was known that the linear electric EM-vibrator is capable to initiate MW-discharge development in the deeply subcritical field of the quasi-optical MW-beam. Such a discharge is localized in the field of EM-vibrator poles. At the same time an efficiency of power interaction of discharge plasma with the EM-field exciting it remained unclear. The scheme of ignition of such a discharge used in the executed works in the air stream has allowed to determine an effective area $\mathbf{S_{ef}}$ of such power interaction. For this purpose distributions of stagnation pressure and stagnation temperature of the flow have been measured in the discharge plasma trail by means of the Pitot tube and thermocouples. Processing of experimental data has shown that $\mathbf{S_{ef}}$ more than by 10 times exceeds the area of the transversal cross-section of plasma discharge area.

- **Personnel Commitments**

Name	Category	Days
Igor I. Esakov	I	22
Kirill V. Khodataev	I	9
Lev P.Grachev	I	22
Konstantin V. Aleksandrov	I	20
Vyacheslav A.Vinogradov	I	15
Alexander A. Ravaev	I	20
Vyacheslav V. Fedorov	I	25
Nikolay I. Uksusov	I	36
Sergey V. Denisyuk	I	25
Tatyana A.Mityaeva	I	20
Tamara M. Murinchik	II	20
Andrey A. Kostyuk	II	6
Dmitry V. Bychkov	II	13
Sergey N. Il'in	III	16
Igor V. Prutskiy	III	16

Task 9: Development, design and manufacturing of facility elements allowing to realize SS submerged stream of propane-air mixture in the given composition proportion

Carried out experiments within the limits of **theTask 7** were spent under the scheme in which the initiator of the MW-discharge was tubular and its central channel was an outlet section of a formation duct of the high-speed combustible propane-air mixture. As it was specified, this scheme was characterized by the thermal blocking effect. The scheme of creation of the isobaric submerged high-speed flammable mixture stream has been developed for liquidation of this disadvantage within the limits of the present problem. Its elements have been developed, allowing to change propane percentage in this mixture, they are manufactured and mounted.

- **Personnel Commitments**

Name	Category	Days
Igor I. Esakov	I	22
Kirill V. Khodataev	I	9
Lev P.Grachev	I	22
Konstantin V. Aleksandrov	I	20
Vyacheslav A.Vinogradov	I	15
Alexander A. Ravaev	I	20
Vyacheslav V. Fedorov	I	25
Nikolay I. Uksusov	I	36
Viktor A. Gudovich	I	20
Tatyana A.Mityaeva	I	20
Tamara M. Murinchik	II	20
Andrey A. Kostyuk	II	6
Dmitry V. Bychkov	II	13
Sergey N. Il'in	III	16
Igor V. Prutskiy	III	16

Task 10: Measurements of flat SS submerged stream parameters in the working part of the setup. The stream is of air flowing from the atmosphere

Within the limits of **the Task 4** the duct of formation of the flat submerged high-speed stream has been designed, manufactured and mounted. At performance of the present problem parameters of this stream in the working chamber of the installation have been investigated. The Pitot tube measuring local values of a stream stagnation pressure has been manufactured for this purpose. The device of its moving is developed and manufactured. Measurements in a near zone of the outlet Laval nozzle of the flow duct have shown that on its exit the stream with the calculated parameters is formed: in the section (10 x 70) mm the Mach number is M = 2 at v_{fl} = 500 m/s, p_{st} = 100 Torr and T_{st} = 150 m/s. These parameters with the given section remain on the length of the stream of scale 100 mm.

- **Personnel Commitments**

Name	Category	Days
Igor I. Esakov	I	22
Kirill V. Khodataev	I	9
Lev P.Grachev	I	22
Konstantin V. Aleksandrov	I	20
Vyacheslav A. Vinogradov	I	15
Alexander A. Ravaev	I	20
Vyacheslav V. Fedorov	I	25
Nikolay I. Uksusov	I	36
Viktor A. Gudovich	I	20
Tatyana A.Mityaeva	I	20
Tamara M. Murinchik	II	20
Andrey A. Kostyuk	II	6
Dmitry V. Bychkov	II	13

Sergey N.Il'in	III	16
Igor V. Prutskiy	III	16

Task 11: Experiments on realization of MW discharge initiated by the vibrator, when the vibrator is excited by "thin quasi-optical EM beam"

In the working chamber of the experimental installation the quasi-optical EM-beam is realized by the horn aerial with the size of the outlet aperture 90 x 90 mm. In the majority of experiments the linear EM-vibrator initiating MW-discharge is placed along a vector of an electric component of the EM-beam on its axis and on an axis of the high-speed gas stream. Linear EM-vibrators have scales $2L \leq 60$ mm. In such a situation an electrodynamic excitation of the EM-vibrator occurs on all its length. Within the limits of the present problem the vibrator excitation was investigated only on its separate site. In experiments the vibrator was located in the high-speed stream of air, and its ability to initiate the MW-discharge was determined. Thus in the first statement it was gradually displaced from the EM-beam center, that is as though it was moved out of the field area exciting it. In the second statement the EM-wave falling on the vibrator partially was shielded by an absorber. Thus the vibrator was excited only over the central area and the length of this area was varied. As a result of experiments corresponding functional dependences are obtained.

- **Personnel Commitments**

Name	Category	Days
Igor I. Esakov	I	22
Kirill V. Khodataev	I	9
Lev P.Grachev	I	22
Konstantin V. Aleksandrov	I	20
Vyacheslav A.Vinogradov	I	15
Alexander A. Ravaev	I	20
Vyacheslav V. Fedorov	I	30
Nikolay I. Uksusov	I	36
Viktor A. Gudovich	I	20
Tatyana A.Mityaeva	I	20
Tamara M. Murinchik	II	20
Andrey A. Kostyuk	II	6
Dmitry V. Bychkov	II	13
Sergey N. Il'in	III	16
Igor V. Prutskiy	III	16

Task 12: Development, design and manufacturing of a gas-dynamical system for heating air and SS nozzle destined for forming the submerged stream with required parameters

The executed experiments on research of deeply subcritical MW – discharge plasma influence on characteristics propane-air mixture burning were carried out in the high-speed "cold" stream of this mixture. The static temperature of gas in this stream was equal to 150 °K. Naturally, there is a question what this influence will be in a "warm" stream, at a "room" temperature of gas in it. Within the limits of the present problem the equipment for ensuring of a warm stream in the working chamber of the installation has been developed, designed and manufactured. Conservation of gas speed $v_{fl} = 150$ m/s in the was thus supposed. Change of the Mach number on an exit of the stream formation duct has required development of also another Laval nozzle. It has been developed and manufactured.

- **Personnel Commitments**

Name	Category	Days
Igor I. Esakov	I	22
Kirill V. Khodataev	I	9

Lev P.Grachev	I	22
Konstantin V. Aleksandrov	I	20
Vyacheslav A.Vinogradov	I	15
Alexander A. Ravaev	I	20
Vyacheslav V. Fedorov	I	30
Nikolay I. Uksusov	I	40
Tatyana A.Mityaeva	I	20
Tamara M. Murinchik	II	20
Andrey A. Kostyuk	II	6
Dmitry V. Bychkov	II	15
Sergey N. Il'in	III	20
Igor V. Prutskiy	III	20

Task 13: Theoretical support of experiments

Within the limits of this problem theoretical support of the experimental program performance was conducted. Plasma-chemical reactions in combustible propane-air mixture at of burning in it of the microwave discharge, influencing process of propane burning have been considered. The theoretical model of deeply subcritical MW- discharge in the high-speed stream of warm air has been developed. Necessity of such a model is connected with the fact that at conservation of v_{fl} in the submerged air stream its static pressure rises and the discharge has to burn at this raised pressure. Numerical modeling of linear system of deeply subcritical MW-discharges initiated by parallel EM-vibrators has been executed. The distance between vibrators and its influence on burning uniformity of discharges along this system thus varied.

- **Personnel Commitments**

Name	Category	Days
Kirill V. Khodataev	I	56
Konstantin V. Aleksandrov	I	20
Vyacheslav A.Vinogradov	I	60
Alexander A. Ravaev	I	40
Andrey A. Kostyuk	II	40

Task 14: Experiments on determination of flame front propagation velocity over propane-air flammable mixture, ignited by deeply undercritical MW discharge initiated by the vibrator in SS flow

According to **the Task 7** experiments on research of deeply subcritical MW-discharge plasma influence on parameters of propane-air mixture burning in its high-speed stream in the scheme when the internal aperture of the MW-discharge initiator is an outlet section of a stream formation duct have been made. Researches on the given problem were carried out in the scheme when the initiator of the MW-discharge was located in the submerged high-speed stream of propane -air mixture. Originally the formation duct of this stream has been added by an element allowing to change a stream speed $\mathbf{v_{fl}}$ on its exit from several tens m/s to maximum v_{fl} = 500 m/s. Corresponding diagnostic means have allowed to determine the stream characteristics in this range $\mathbf{v_{fl}}$ in experiments**.** In the basic experimental series characteristics of initiated deeply subcritical MW-discharge in air stream have been investigated at a variation of $\mathbf{v_{fl}}$. As a result of them it was found out that the gas temperature of air $\mathbf{T_{st}}$ which has leaked over the discharge is smaller than temperature of inflammation of propane-air mixture necessary for its ignition by traditional means. At the same time the MW-discharge ignited such mixture which has passed over its plasma volume. Essentially lean mixture was thus ignited also and to $\mathbf{v_{fl}}$ scale 200-300 m/s propane in the mixture was burnt down completely. Besides, in the area adjoining to the discharge, in the transversal cross-section of a stream the speed of a flame front propagation was essentially higher the "traditional" speed.

- **Personnel Commitments**

Name	Category	Days
Igor I. Esakov	I	25
Kirill V. Khodataev	I	5
Lev P.Grachev	I	25
Konstantin V. Aleksandrov	I	25
Vyacheslav A.Vinogradov	I	15
Alexander A. Ravaev	I	20
Vyacheslav V. Fedorov	I	25
Nikolay I. Uksusov	I	35
Sergey V. Denisyuk	I	16
Tatyana A.Mityaeva	I	16
Tamara M. Murinchik	II	15
Andrey A. Kostyuk	II	21
Sergey N. Il'in	III	30

Task 15: Realization of multiple ignition of propane-air mixture with a help of the system of MW deeply undercritical discharges initiated by the vibrators in SS flow

According to **Task 4** and **Task 10** experimental installation has been completed by the elements allowing in its working chamber to realize a flat submerged high-speed air stream. Within the limits of the present problem originally in this stream has been carried out multiple lighting of the initiated MW-discharges. Thus at an arrangement of EM-initiators over the screen in loops of EM-waves distances Δ between them in a grid were large enough, no smaller than 15 mm. An additional series of experiments has shown that at approach of EM-vibrators to the screen their mutual electrodynamic influence decreases. It has allowed to increase a number of EM-vibrators being in the stream, by reducing of the size Δ. With such grid we have carried out multiple lightning of deeply subcritical MW-discharges both in the high-speed stream of pure air, and in its gas mixture with propane. Thus MW-discharges ignited this gas mixture.

- **Personnel Commitments**

Name	Category	Days
Igor I. Esakov	I	25
Kirill V. Khodataev	I	5
Lev P.Grachev	I	25
Konstantin V. Aleksandrov	I	25
Vyacheslav A.Vinogradov	I	15
Alexander A. Ravaev	I	20
Vyacheslav V. Fedorov	I	25
Nikolay I. Uksusov	I	35
Sergey V. Denisyuk	I	16
Tatyana A.Mityaeva	I	16
Tamara M. Murinchik	II	15
Andrey A. Kostyuk	II	21
Sergey N. Il'in	III	30

Tasks 16-19:

- **Mounting and testing of elements located at the inlet of the track forming SS stream insuring the undertaking of experiments with airflow at higher air temperature, pressure and Mach number;**
- **Investigations of SS submerged stream with higher temperature parameters in the working part of the setup;**
- **Development, design, manufacturing and testing of initiating electromagnetic vibrator assigned for work in the heated SS flow;**
- **Experiments on creation of deeply undercritical MW discharge initiated by the vibrator in SS air stream with higher temperature, pressure and Mach number**

Within the limits of **the Task 12** elements have been developed for realization in the working chamber of the installation of the warm submerged high-speed stream of air. At performance of the present problem an installation of the formation duct of such stream has been carried out. This duct has been tested. Tests were carried out by means of local measuring instruments $\mathbf{T_{stag}}$ and $\mathbf{p_{stag}}$, executed on the basis of the thermocouple and Pitot tube. Determination of the stream switching on delay time **Δt** concerning time of switching on of the heater located on an inlet of its formation duct was one of test objectives. Experiments were spent by means of a thermocouple measuring instrument. They have shown that the gas temperature in the outlet stream approximately linearly grows depending on **Δt** and appearance on calculated parameters of the stream occurs at $\Delta t \approx 10$ s. The further experiments have shown, as in warm stream the linear EM-vibrator initiates the MW-discharge in deeply subcritical field of the quasi-optical EM-beam. Thus the basic characteristics of the MW-discharge in the warm high-speed stream as a first approximation remain the same, as well as in the cold stream. Results of works performance on these problems have shown, that the installation allows to carry out research of deeply subcritical MW-discharge plasma influence on processes of propane-air mixture burning in its high-speed warm stream.

- **Personnel Commitments**

Name	Category	Days
Igor I. Esakov	I	70
Kirill V. Khodataev	I	20
Lev P.Grachev	I	70
Konstantin V. Aleksandrov	I	69
Vyacheslav A.Vinogradov	I	50
Alexander A. Ravaev	I	70
Vyacheslav V. Fedorov	I	86
Nikolay I. Uksusov	I	114
Sergey V. Denisyuk	I	18
Viktor A. Gudovich	I	60
Tatyana A.Mityaeva	I	60
Tamara M. Murinchik	II	60
Andrey A. Kostyuk	II	22
Dmitry V. Bychkov	II	70
Sergey N. Il'in	III	25
Igor V. Prutskiy	III	85

Task 20: Theoretical support of experiments

Within the limits of the present problem theoretical support of experiments was conducted. Numerical modeling of ignition and burning of propane-air mixture in its high-speed stream in the presence of microwave streamer deeply subcritical discharge was thus carried out. Also the static temperature of gas from its "room" value to 150 °K thus varied. The modeling has shown, that on processes of burning of the given mixture impact plasma chemical processes in discharge plasma including hard ultra-violet radiation.

- **Personnel Commitments**

Name	Category	Days
Kirill V. Khodataev	I	60
Vyacheslav A.Vinogradov	I	40
Alexander A. Ravaev	I	16

Task 0.: Project Management

- **Fulfilled work**

Distribution of tasks between participants of the project, work coordination, the control of terms and quality of performance of tasks and the account of the executed works.

- **Personnel Commitments**

Name	Category	Days
Igor I.Esakov	I	84
Lev P.Grachev	I	80
Kirill V. Khodataev	I	17
Tamara M. Murinchik	II	60

3. Summary of Personnel Commitments

	Number of persons	Total days	Total grants, USD
Category I	11	4 446	131 250
Category II	3	664	16 600
Category III	4	470	14 250
Category IV	-	-	-
Total		5 580	162 100

4. Presentation of project results

see Attachment 1. List of published papers and reports without abstracts
see Attachment 2. List of presentations at conferences and meetings without abstracts
see Attachment 3. Information on patents and copy rights

5. Co-operation with foreign collaborators/partners

The Project is the Partner one.
Partner:
The European Office of Aerospace Research and Development (EOARD). 86 Blenheim Crescent, Middlesex Ruislip, HA4 7HB, United Kingdom.

The person possessing the right to sign: Susan Fuller, Tel.: +44(0)1895616146; Fax: +44(0)1895616012; e-mail: susan.fuller@london.af.mil.

The person responsible for contacts under the project: Surya Surampudi,
Tel.: +44(0)189 5616012, fax: +44(0)1895616012, e-mail: Surya.surampudi@london.af.mil

In project performance continuous working contracts were carried out with representatives of the Partner by e-mail. Detailed discussions of the working materials received during works under the Project, intermediate results and prospects of development of directions of researches have been carried out during personal meetings including:

In January of 2007 at International Conference in Reno with participation of Julian Tishkoff (AFOSR), David Van Wie (JHU), Surya Surampudi (EOARD).

In April of 2007 in MRTI RAS with participation of Julian Tishkoff (AFOSR), Surya Surampudi (EOARD), Suh Gill Won (ISTC).

In January of 2008 at International Conference in Reno with participation of Julian Tishkoff (AFOSR), David Van Wie (JHU), Surya Surampudi (EOARD).

In May of 2008 in St-Petersburg and Moscow in MRTI with participation of Julian Tishkoff (AFOSR), David Van Wie (JHU), Surya Surampudi (EOARD), Suh Gill Won (ISTC) .

In January of 2009 at International Conference in Orlando with participation of Julian Tishkoff (AFOSR), David Van Wie (JHU), Campbell Carter (AFRL/PRAS).

In March of 2009 in MRTI RAS with participation of Julian Tishkoff (AFOSR), Surya Surampudi (EOARD), Suchomel Charles Frank (AFRL), Campbell Carter (AFRL/PRAS), Datta V. Gaitonde (AFRL/VAAA), Suh Gill Won (ISTC).

6. Co-operation with CIS sub-contractors

There are no Subcontractors in CIS.

7. Procurement

Work plan No.	Name	Status
2E	Communicator Qtec S200	Obtained 18.12.06
5E	Tripod Manfrotto 055PROB	Obtained 18.12.06
6E	Flip char Medium Standard 100 x 65 cm.	Obtained 18.12.06
3E	Spectrometer AvaSpec-2048FT	Obtained 22.01.07
4E	AvaSoft-Full, Spectrometer software version 7.0 OceanOptics	Obtained 22.01.07
Over the Workplan	Smart UPS 1000VA Power Pro (Ippon)	Obtained 21.05.07
1E	ASUS F3Sa: Core 2 Duo-T7500-2200MHz/RAM 2048Mb DDR2/HDD 250Gb/DVD+-RW/SB/Video ATI Radeon X2400 128 Mb/FM/GLAN/iEEE1394/WiFi/Bluetooth/Camera/GradReader/15.4” WXGA (1280x800)/Spk/Win’Vista HP/Bag/Mouse Optical USB	Obtained 14.03.08
4E	LCD-Monitor 20” ViewSonic VP2030b	Obtained 14.03.08
5E	Copier Canon FC-128(A4) with E16	Obtained 14.03.08
6E	Scanner Epson Perfection V200 Photo	Obtained 14.03.08
6E	Scanner Epson Perfection V200 Photo	Obtained 14.03.08
2E	Digital Photocamera Nicon D80 Kit (18-135 mm.)	Obtained 14.03.08
7E	МК-103-100-3М «Электрокомпрессор»	Obtained 06.05. 08
3E	Oscilloscope GDS-820S	Obtained 14.05.08
5E	Oscilloscope Instek GDS-820C	Obtained 17.02.09
1M	Digital multimeterAPPA 207 USB	Obtained 17.02.09
1E	Digital videocamera Sony DCR-SR220E	Obtained 03.03.09
3E	Lenz NIKON AF-S 70-300mm f/4.5-5.6 G VR	Obtained 03.03.09
4E	Lenz NIKON AF-S 105mm f/2.8 VR Micro	Obtained 03.03.09
6E	LCD-Monitor 19” ViewSonic VA926	Obtained 03.03.09
6E	LCD-Monitor 19” ViewSonic VA926	Obtained 03.03.09
Over the Workplan	Core 2 Duo-E5400-2700MHz/800MHz/2x1Mb DDRIIRAM DIMM 1024Mb PC6400/HDD 250Gb (7.200RPM) (S-ATA-II)/DVD+-RW (S-ATA)/Video GeForce 9500GT 512Mb TV+DVI PCI-E/Case ATX/Keyboard PS/2/Mouse Optical USB/MS Win’XP HE SP3 Rus	Obtained 09.06.09

8. Conclusion, Problems, Suggestions

The executed researches are fundamental physical researches.

Results of the executed researches will be used as comparative at performance of similar researches in a warm high-speed stream. The obtained results allow to analyze possibilities of their practical application in various practical areas.

Attachment 1: List of published papers and reports

1. *Investigation of deeply undercrirical microwave discharge plasma influence on combustion process in propane-air mixture in its high-speed flow*. Annual Technical Report on Project ISTC #3572. 2007.
2. *Investigation of deeply undercrirical microwave discharge plasma influence on combustion process in propane-air mixture in its high-speed flow*. Annual Technical Report on Project ISTC #3572. 2008.
3. Khodataev K., Esakov I., Grachev L. and Van Wie D. *Microwave Discharge in Quasi-optical Wave Beam* //45th AIAA Aerospace Sciences Meeting and Exhibit (8-11 January 2007, Reno, Nevada). -AIAA 2007-0433.
4. Bychkov D.V., Grachev L.P., Esakov I.I. *Initiated MW-discharfe in the supersonic air stream excited by deeply subcritical field of quasi-optical electromagnetic beam* //Collection of reports abstracts of XXXV International (Zvenigorod) Conference on plasma physics and CNF, 11-15 February 2008. -C.312.
5. Esakov I., Grachev L., Khodataev K., Vinigradov V. and Van Wie D. *Deeply Subcritical MW Discharge in the Submerged Stream of Propane-Air Mixture* //46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 7-10 Jan. 2008. -AIAA 2008-1403.
6. Bychkov D.V., Grachev L.P., Esakov I.I. *Deeply subcritical MW – discharge excited by the field of quasi-optical electromagnetic beam in the supersonic air stream* //Zhurnal Tekhnicheskoi Fiziki. -2009. -V.79, N.3. -P.39-45.
7. Bychkov Dmitry V., Esakov Igor I., Grachev Lev P., Khodataev Kirill V., Van Wie D.M. *Electrical discharge in deeply subcritical field of MW beam in a high-speed air stream and in propane-air mixture* //47th AIAA Aerospace Sciences Meeting and Exhibit, Orlando, USA, 7-10 Jan. 2009. -AIAA Paper 2009-1551.
8. Bychkov D.V., Grachev L.P., Esakov I.I., Ravaev A.A., Severinov L.G. *Electric discharge in deeply subcritical field of MW –beam in the high-speed stream of air and its mixture with propane* //Zhurnal Tekhnicheskoi Fiziki. -2009. -V.79, N.9. -P.33-40.

Attachment 2: List of presentations at conferences and meetings

1. Khodataev K., Esakov I., Grachev L. and Van Wie D. *Microwave Discharge in Quasi-optical Wave Beam* //45th AIAA Aerospace Sciences Meeting and Exhibit (8-11 January 2007, Reno, Nevada).
2. Esakov I., Grachev L., Khodataev K., Vinigradov V. and Van Wie D. *Deeply Subcritical MW Discharge in the Submerged Stream of Propane-Air Mixture* //46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 7-10 Jan. 2008.
3. Bychkov Dmitry V., Esakov Igor I., Grachev Lev P., Khodataev Kirill

V., Van Wie D.M. *Electrical discharge in deeply subcritical field of MW beam in a high-speed air stream and in propane-air mixture* //47th AIAA Aerospace Sciences Meeting and Exhibit, Orlando, USA, 7-10 Jan. 2009.